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ABSTRACT

This report presents examples of Rand's current research in the information sciences and illustrates the application of information science tools to specific policy studies. The projects discussed depict Rand's success with using corporate seed money to bridge the gap between the research and development of new information science tools and techniques, and the application of those tools to current policy analysis issues. Some of the Rand corporation's major past accomplishments in this area are cited. Examples of Rand's current research agenda include: (1) an interactive algebra tutor; (2) an expert system designed to assist claims adjustors in asbestos litigation; (3) a database management system applied to a network of emergency communication stations; and (4) strategic and tactical war gaming applications. Ideas for future research dealing with new challenges in the information sciences are presented, e.g., new database structures and the integration of artificial intelligence techniques with both databases and user-computer interfaces. (CGD)

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A RAND NOTE

N-2555-RC

Recent Contributions of Information Sciences Research at RAND to Modeling- and Simulation-Based Policy Analysis

G. L. Donohue, K. Poehlmann, M. Vaiana

March 1987

RAND

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PREFACE

In this Note the authors present examples of RAND's current research in the field of information sciences and illustrate the application of information science tools to specific policy studies.

Although RAND's research environment is characterized by a strong link between research and application, such a linkage does not necessarily characterize the attitudes of those who sponsor RAND projects. Sponsors of policy research are often reluctant to fund the development of new tools to use with policy issues. On the other hand, those who wish to build new computer science tools may be reluctant to fund a project that addresses policy issues, because they wish to concentrate on developing the tool itself. To bridge this gap, and in anticipation of future outside support, RAND has invested corporate seed funds over the past five years to ensure that the synergism between research and application is maintained.

The projects discussed herein illustrate RAND's success with using corporate seed money in this way and represent research conducted across several RAND departments. These projects were described in a briefing to the trustees of the Systems Development Foundation (SDF) in July 1986 at RAND. The object of the briefing was to show how SDF funding was being used at RAND to further information science research. This Note documents the content of that briefing.

SUMMARY

The RAND Corporation has contributed outstanding research work in the field of information sciences. From the JOHNNIAC computer, one of the earliest interactive systems, to today's powerful graphics tools for simulation, to expert systems, RAND has made its mark.

RAND's current research agenda involves not only the development of new tools and techniques but also applications of those tools to current policy analysis issues. Recent research contributions include work in simulation methodology, parallel processing, and man-machine interface designs. In this Note we present examples of this research: an interactive algebra tutor; an expert system designed to assist claims adjusters in asbestos litigation; a database management system applied to a network of emergency communications stations; and strategic and tactical wargaming applications.

Now, as in the past, RAND provides a unique environment for information sciences research. An ongoing history of pure research has made key artificial intelligence and other computing techniques available to RAND scientists. The scientists have in turn recognized the powerful potential of these techniques and have used them effectively to address a variety of problems. At RAND, the analyst seeking the answer to an important policy question works side by side with computer specialists who strive to build new tools for the analyst's quest.

ACKNOWLEDGMENTS

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I. INTRODUCTION

PAST RAND WORK IN INFORMATION SCIENCES

RAND's long and illustrious history of innovative research in information sciences provides the context for its current work.[1] The range and importance of the corporation's contributions in the area are suggested by the following examples of some of the major accomplishments over the past 30 years:

- IPL-V: The culmination of a series of symbol-manipulating and list-processing languages used in early artificial intelligence work. The concept of list processing originated at RAND and has had tremendous impact on computer science.
- SIMSCRIPT: One of the world's most widely used simulation languages in military, industrial, and social applications.
- The RAND Tablet: The first example of a two-dimensional writing surface for computer communication, with sufficient accuracy to allow recognition of hand-printed characters approximately 1/4 inch high.
- GRAIL: An interactive computing system based on the RAND Tablet which was a major thrust in modeling and interactive systems. GRAIL and its successor, BIOMOD, pioneered the use of graphic displays and tablets as input/output devices.
- JOSS®: One of the first interactive computing systems, it is still used; JOSS led to the development of BASIC and MUMPS.

[1] In this brief overview it is impossible to cite all the valuable research performed by gifted computer scientists at RAND. Their important contributions have gained worldwide recognition. A comprehensive bibliography of publications in Expert Systems and Computing Technology may be obtained on request from the Publications Department, The RAND Corporation, 1700 Main Street, Santa Monica, CA 90406-2138. The systems described in this Note are also featured in Philip Klahr and Donald A. Waterman (eds.), *Expert Systems: Techniques, Tools, and Applications*, Addison-Wesley Publishing Co., 1986. This book also contains many bibliographical entries to aid the interested reader.

- RITA (RAND Intelligent Terminal Agent): One of the very early English-like languages for developing intelligent interfaces to computer systems, used with some success as a tool for heuristic modeling.
- MH: A UNIX-based electronic message handling technique.
- The RAND Video Graphic System: One of the first distributed, time-shared, high-resolution graphics systems.

CURRENT RESEARCH AGENDA

As these past innovations and their descendants move into the commercial environment, RAND's evolving research interests continue to help define the field in information sciences. Our agenda reflects a two-pronged approach: To advance the state-of-the-art in the area, and, equally important, to design more powerful tools to help analysts use computers more effectively to accomplish quality research.

This approach is appropriate in the RAND environment. RAND differs from a good university or industrial laboratory because our efforts to develop new computer tools and techniques are intimately coupled to real-world policy analysis. Computer scientists are frequently criticized for developing solutions that only work on artificially constructed "problems," usually for demonstration purposes. At RAND, the tools we develop are quickly applied to real issues. Often, the tool is inadequate for the task; thus the application helps us to focus our future tool-building efforts in the right direction.

Policy Analysis Support

The nature of our support for policy analysis falls into three basic categories:

- Development of better analytic tools
- Management of large, complex databases
- Laboratories

Much of our effort in the first category is simulation-oriented. Because the policy problems that we seek to simulate are increasingly complex, speed has become a major issue. Speed and transparency are also issues in tactical wargaming, another focus of our tool development activities. Computerized wargames are a cost-effective analog to actual field exercises involving considerable resources in terms of men and materiel. The analyst in this case is not typically a computer scientist but is more often a military planner with many years of field experience. Gaming brings the analyst closer to the type of tactical decisionmaking which occurs in the field by providing methods of real-time interaction with the computer to direct the course of the simulation. Gaming also allows the decisions made by the analyst to become part of the evolving database supporting the game program.

Our work in building expert systems is linked to both gaming and simulation activities. Expert systems are attempts to understand and capture what people do under certain circumstances, what they believe, and how their value systems influence their policy judgments. The information embodied in expert systems then becomes an input to both simulations and games.

Analyzing larger, more complex policy problems entails using very large databases. Our work in this area is designed to make these databases easier to use, to couple them properly to simulations, and to enable the noncomputer analyst to work easily with the databases--for example, to retrieve data in a variety of ways, or to display the data graphically.

To conduct our research, we have invested in three major laboratories:[2] The Information Systems Laboratory, the Military Operations Simulation Facility, and the Strategy Assessment Center. The Information Systems Laboratory is primarily used in basic research to develop and evaluate new tools. The other two laboratories are used for policy analysis at the tactical and strategic level, respectively. Here new tools are implemented and tested against real analytic tasks. The

[2]Since the briefing leading to this Note was given, a fourth laboratory has been added: the Combat Analysis Laboratory.

creation of the Institute for Research on Interactive Systems (IRIS) ensures continuity of RAND's important work in computer science techniques. This Institute tends to look at information system issues from the combined perspectives of the information and behavioral sciences.

Recent Research Contributions

Viewing our work from the research perspective, we can define three major areas of interest:

- Simulation and expert system methodology
- Parallel processing
- Man-machine interface

The first category includes our work on languages--for example, ROSIE® (Rule-Oriented System for Implementing Expertise) and RAND-ABEL®, our two latest expert system languages; ROSS (RAND Object-oriented Simulation System), an English-like language which provides a programming environment in which users can conveniently design, test, and modify large knowledge-based simulations of complex mechanisms; and REDUCE,[3] an algebraic expert system using a symbolic, computation language.

Parallel processing provides a potential solution to the speed problem in simulating complex problems. Our work in this area has concentrated on Time Warp,[4] a type of operating system that promises at least an order of magnitude increase by using asynchronous, loosely-coupled parallel processors.

RAND was a pioneer in efforts to make the man-machine interface more natural and more effective. The JOHNNIAC computer developed at RAND was one of the earliest computers designed for interactivity. We continue to develop interactive tools such as map overlays for terrain

[3]A. C. Hearn, *REDUCE User's Manual*, The RAND Corporation, Publication CP78, April 1985.

[4]D. Jefferson and H. Sowizral, *Fast Concurrent Simulation Using the Time Warp Mechanism, Part I: Local Control*, The RAND Corporation, N-1906-AF, December 1982.

Plate 1—Pact vs. NATO at intra German border

Plate 2—Pact advances and engages NATO units

Plate 3—Man in the loop experiments with tactics

Plate 4—Global view of conflict participation

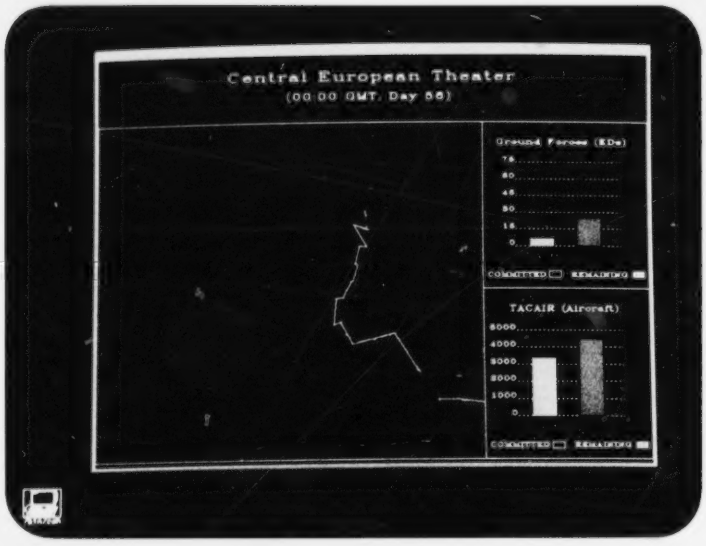

Plate 5—Illustrative Pact forces advancing
(Arrows)

Plate 6—Soviet ICBM and SLBM launch points
(Graphics-simulation integration)

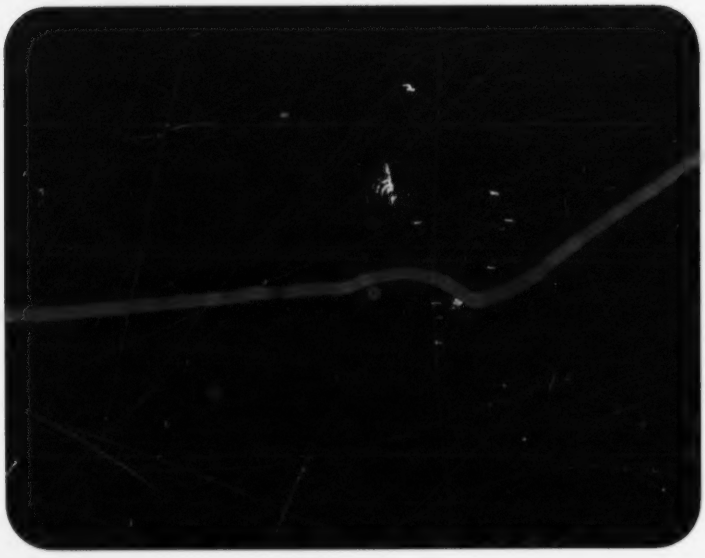

Plate 7—Illustrative SDI satellite configuration vs. boost-phase missiles

Plate 8—Initial position of tank units
(Blue dots)

Plate 9—Airborne radar view of U.S. tanks moving on roads
(Blue dots)

Plate 10—Tank's 360° view
(Grey = obscured by foliage terrain)

analysis, dynamic graphics projections, and menu-selectable simulation variations. These interface tools allow more visibility with respect to the policy issues we address. The analyst at the console has the flexibility to choose scenario elements interactively and see the results on a graphics display without having to learn a complex program.

II. EXAMPLES OF APPLICATIONS

In this section, we describe three areas in which we have applied advanced computer tools to specific policy problems: education, legal research, and national security.

EDUCATION

The growing ratio of students to teachers concerns many education experts. We are assessing whether computers can, in effect, reduce that ratio by reducing a given teacher's load. We chose algebra as the test case for this evaluation. Some academically disadvantaged students require greater than average interaction with the teacher to learn algebra. The data show that unless these students learn algebra during the years allotted for it in the school schedule, they never learn it. As a consequence, they do not gain the reasoning ability that learning algebra usually instills.

To investigate whether computers can help teach students algebra, we have designed a LISP-based expert system similar to REDUCE to serve as an algebra tutor and implemented it in a pilot program at Santa Monica High School. As part of this expert system, we are using REDUCE, because it is a very efficient computation approach for solving algebra- or calculus-like problems.

Figure 1 shows one of the students in the program interacting with the expert system. The system presents her with an algebra problem. She tries to solve it, using a graphics tablet interface to talk to the computer. The computer checks to see whether she is solving the problem correctly. If she is not, it tells her where her reasoning error was and shows her ways to solve the problem.

Although we are only in the initial year of this three-year project, we have already learned some important things about man-machine interaction. For example, we discovered early in the program that students find the "mouse" interface unnatural. They much prefer writing with a pencil-like instrument. To make this possible, we built on earlier research with the RAND Tablet and added pattern recognition algorithms to this expert system.

Fig. 1--Algebra tutoring

LEGAL RESEARCH

Three expert systems in the legal domain have been developed at RAND: LDS,[1] a generalized system for determining product liability; SAL,[2] a prototype system based on LDS for evaluation of liability claims

[1]D. A. Waterman and M. A. Peterson, *Models of Legal Decisionmaking*, The RAND Corporation, R-2717-ICJ, 1981. A shortened version appears as "Rule-Based Models of Legal Expertise," *Proceedings of the First Annual National Conference on Artificial Intelligence*, Palo Alto, 1980, pp. 272-275.

[2]J. Paul, D. A. Waterman, M. Peterson, and J. Kipps, "SAL: An Expert System for Evaluating Asbestos Claims," *Proceedings of the First Australian Artificial Intelligence Congress*, Melbourne, Australia, November 17-21, 1986.

related to asbestos litigation; and EPS, a system currently under development for estate planning. Here we consider the SAL system in more detail. Courts at every level are clogged with cases. Our basic research question is whether expert systems can relieve the backlog by helping lawyers to select those cases whose characteristics make them fairly unambiguous and thus candidates for quick settlement.

SAL: System for Asbestos Litigation

It has been estimated that about 21 million people have been exposed to harmful asbestos. Of that, perhaps as many as 200,000 people may die from asbestos exposure, and there is currently a backlog of some 20,000 court cases in the legal system. These cases are difficult and time-consuming to try because the nature of the medical evidence is not always clear, and because asbestos-related disease may become active many years after exposure. Also, judgments appear to be uneven. The awards for apparently similar cases may differ significantly in different parts of the country.

Our research question is whether we can systematize what we know about the history of past cases and the characteristics of successful cases, and by embodying that knowledge in an expert system, provide lawyers and claims adjusters with an organized overview of a case before it gets into the legal system. For complex, high-stakes lawsuits, we want to identify important issues and their relationships and determine the probable outcome of the case. We need a way to justify the settlement position and suggest potential actions. Expert systems provide a way to combine information from several sources, in this case medical as well as legal, to minimize uncertainties arising from ambiguous medical evidence, time lag between exposure and symptoms, and financial responsibilities.

The current expert system, which contains about 400 rules, is merely a prototype which we are using to gain a deeper understanding of the process of case evaluation and its relation to legal decisionmaking. The final system, which could be used in a variety of court environments, will require 1000 to 1500 rules. The prototype uses ROSIE, an expert system building language developed at RAND. ROSIE's English-like syntax and the forward-backward logic chaining make it particularly appropriate for this sort of legal application.

Figure 2 shows what a lawyer or claims adjuster might see when working with the system. The user communicates with SAL via a collection of pop-up windows and programmable menus. The scrollable windows appear only when needed. First, the computer prompts the lawyer to answer approximately 25 queries. The first few are shown here in the upper left window. As the questions are answered, the list scrolls to reveal additional text. The lawyer is asked to supply information such as the name of the client, his age, types of symptoms exhibited, and so forth.

The computer provides more detailed information when the user requests it. For example, the box in the lower right-hand corner provides a scrolling selection menu listing all the types of symptoms indicative of asbestos damage. The lawyer interacts with the computer, selecting each symptom pertaining to the plaintiff's condition. This is shown in the Selection Menu by the symbol <= next to each symptom

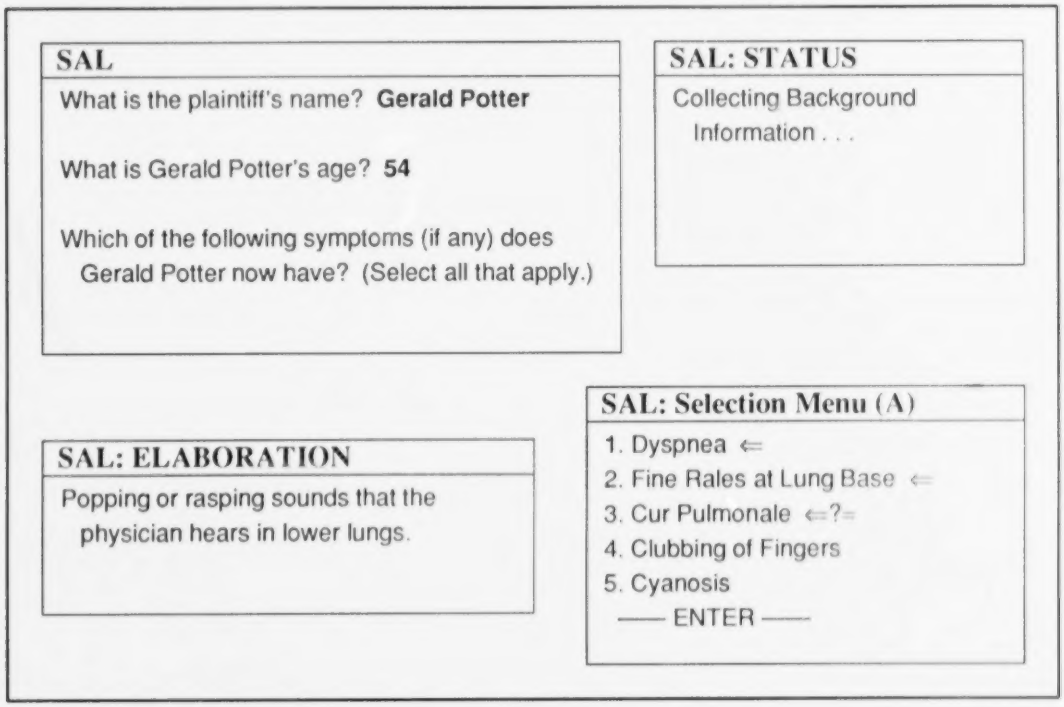
SAL
What is the plaintiff's name? Gerald Potter
What is Gerald Potter's age? 54
Which of the following symptoms (if any) does Gerald Potter now have? (Select all that apply.)
SAL: STATUS
Collecting Background Information . . .
SAL: Selection Menu (A)
1. Dyspnea ⇐
2. Fine Rales at Lung Base ⇐
3. Cur Pulmonale ⇐?=
4. Clubbing of Fingers
5. Cyanosis
—— ENTER ——
SAL: ELABORATION
Popping or rasping sounds that the physician hears in lower lungs.

Fig. 2 -- Program prompts for case history/symptoms

chosen as applicable to this client. Perhaps the lawyer has a question about the definition of a particular symptom. A signal to the computer provides an explanation in layman's terms of any symptom. In Fig. 2, symptom number 3 has been chosen for further elaboration, as shown by the symbol <=?=.

Once the 25 queries are answered, the system presents 80 to 100 conclusions in a scrollable window about the probable outcome of the case, based on its characteristics. Figure 3 shows an example in which there appears to be a good chance of getting a favorable outcome. The user can query the system to get more information, as shown by the selection character <= in the Explanation Menu. Asked for an example, the system provides an estimate of the probable value of the award. The user is shown what the range of that award might be as opposed to just a mean estimate. Or the user can ask the system to provide an explanation of the rules that it used to arrive at the estimate, as shown in Fig. 4.

Because ROSIE is an English-like language, the system can provide the user with a clearly stated English-like explanation. The system is thus rich, flexible, and transparent. Another application of this expert system framework is toxic waste injury litigation. ROSIE has also been used for combat intelligence analysis and geopolitical wargaming. It is less successful in those applications because they require up to tens of thousands of rules. It was the need for a faster, more efficient language than ROSIE for wargaming that led to the development of RAND-ABEL, discussed below.

NATIONAL SECURITY APPLICATIONS

National Emergency Communications

The first example of a national security application is a study (Project AMBER) of a new national emergency communication system that would use existing AM broadcast stations. The issue here is, of course, ensuring that emergency messages are sent rapidly and reliably through the network when necessary.

This kind of study requires very large communications and geographic databases. To make these data easy for the analyst to use, we have connected the databases directly to graphics interfaces. For

SAL: CONCLUSIONS AND ACTIONS

1. "Gerald Potter" does possess "complete evidence of asbestosis"
2. The value of "the case" is 237300.0 DOLLARS ⇐
3. The disability-compensation of "the case" is 97750.0 DOLLARS
4. The personal-characteristic-adjustment of "the case" is 1.2

SAL: RESULT

[Case Description]

Plaintiff: Gerald Potter
Value of Case: 237000 DOLLARS
Range:
Low: 225000 DOLLARS
High: 249000 DOLLARS

Explanation Menu

1. Description
2. Example ⇐
3. Premises
4. Rule
5. Ruleset
6. Summary
7. Tutorial
8. Why?
9. RETURN

Fig. 3 -- Computation and display of results

SAL: EXPLANATION

LEVEL 1
I concluded that the value of "the case" is 237300.0 DOLLARS

in To EVALUATE-THE-CASE rule 5

because:
The value of the case is the sum of the amounts awarded for injury, disability, and aggravation, as adjusted by considerations of the personal characteristics of the plaintiff.

Here we find the value of the case to be 237300.0 DOLLARS by combining the injury value (100000 DOLLARS) the disability compensation (97750.0 DOLLARS) and the aggravation value (0 DOLLARS).

This total (197750.0 DOLLARS) is adjusted (multiplied) by the personal characteristic adjustment (1.2) yielding the final value.

Fig. 4 -- Request for rule-based elements

this application, we use a very extensive geographic database--roughly 100 million bytes of information just in geographic mapping--that can be easily manipulated by the analyst. These maps have about 30-meter resolution.

Figure 5 shows one of the ways in which the graphics displays provide the analyst with a better overall understanding of the problem. It shows the merging of two databases--the Federal Communications Commission (FCC) database overlaid with the graphics database displaying the location of all the AM broadcasting stations in the United States. The display quickly shows that there are many stations to choose from in the eastern states. However, in the west, the distribution is much sparser, and greater care must be used in selecting stations. Current work will eventually allow the analyst to superimpose network displays of linked stations based on transmission characteristics such as frequency and range.

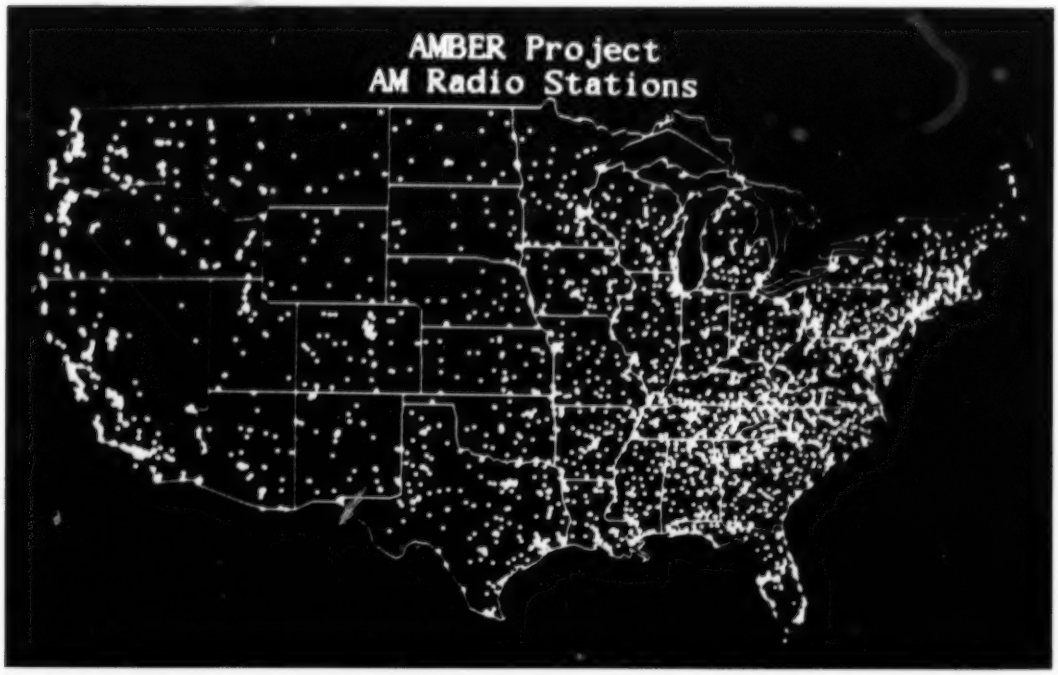

Fig. 5--Example of graphics/database integration

One of the decisions we have to make is which of these radio stations would in fact be equipped with the kind of communication gear that would support a nationwide emergency communication network. Figure 6 shows the result of a simple query that can help inform this decision. It shows the distribution of radio stations in three selected states.

Theater Combat Gaming and Simulation

Another national security application is in the area of theater combat gaming and simulation, with a human interacting with the simulation. The computer here is, in fact, a network of three computers connected together over a high bandwidth local area network to represent Red and Blue forces and a central "control" computer to monitor the game. Conventional war in central Europe is simulated. This particular FORTRAN model simulation takes a Warsaw Pact view of the conflict, and

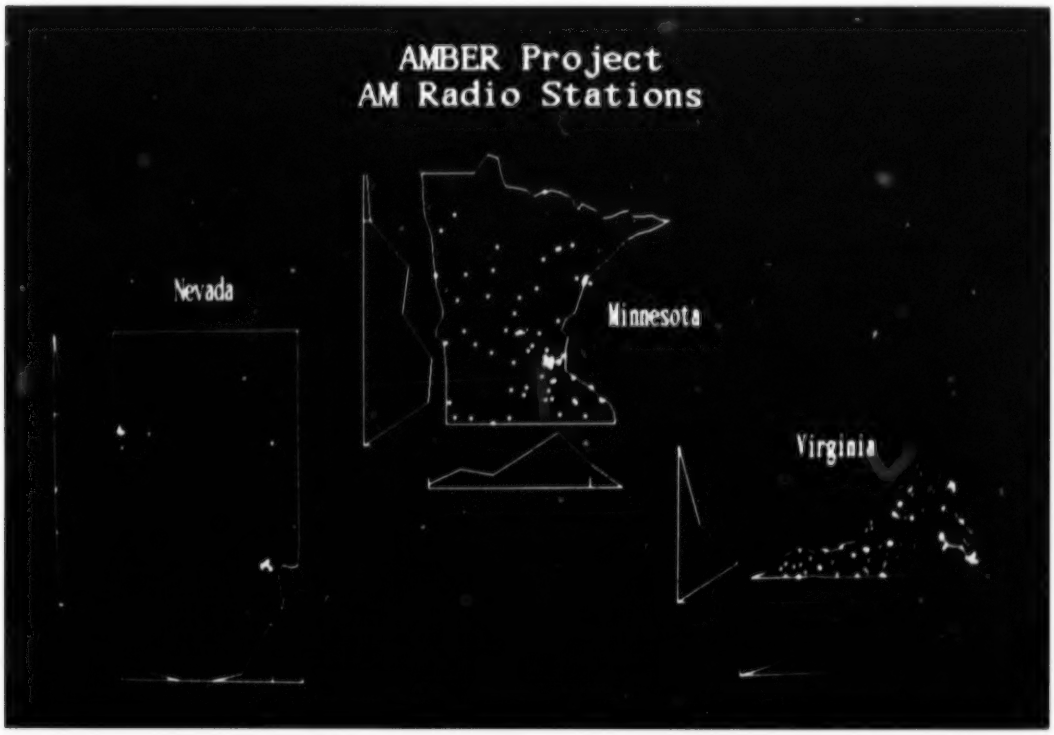

Fig. 6--Station density by latitude and longitude

we have a three-star Army general who is assuming the role of a Warsaw Pact commander. The purpose of the exercise is to evaluate some new tactics that NATO is considering to combat the Pact's thrusts. We are attempting to understand the rules that our commanders use in implementing such tactics so that we can capture that information in an expert system.

Color Plate 1 shows the relative corps boundaries in the central region at the intra-German border as the simulation begins on day zero. Different colors represent different types of terrain contained in the model. To assist his decisions, the player can overlay a wide range of detail on this display. For example, he can look at road networks, rivers, urban areas, etc.

A typical simulation lasts approximately six (simulated) days. Color Plates 2 and 3 show the progress of the war. We can see the Red Warsaw Pact forces advance across the intra-German border, engaging the Blue NATO forces in different areas; we see how the Blue forces move around, trying, at the Blue commander's orders, to counter the Pact's attack.

These types of games are both data intensive and computationally intensive. They take a long time to play and are quite costly in computer time. The need for higher speed in processing and database access methods has led us to develop new tools and system architectures to cope with increasingly complex models. We recognize analyst requirements for quick feedback of results by providing graphics tools which interface with these models and databases. The displays offer an interactive means for the analyst to evaluate results in a variety of ways.

Strategy Assessment Gaming and Simulation

Often, the analyst is interested in geopolitical war, not just war in a particular theater. The expert system needed to explore these issues required thousands of rules, and we found that the initial language, ROSIE, was not sufficiently fast or efficient. We developed RAND-ABEL to overcome these limitations. Rather than ROSIE's emphasis on English-like statements, RAND-ABEL introduces concepts such as two-

dimensional statements that exploit the native English-speaker's ability to understand tables of information. By programming decision tables and hierarchical tables of orders using these tabular statements, we have been able to create large-scale simulations that are efficient and that can be read and understood by application specialists who are not programmers.

Color Plate 4 displays the game board for a worldwide geopolitical simulation. Color Plate 5 shows the movement of the FLOT, or Forward Line of Own Troops, from East Germany into West Germany. The arrows indicate the direction of the advance against the corps structure of NATO. Two of a variety of supportive displays are shown sharing the screen with the FLOT display, at the right-hand side. In this case, however, even though there is almost as much detail represented in the individual combat as in the previous game, the players are the computers themselves. That is, an expert system in which we have tried to capture the logic of the Warsaw Pact force commander plays against an expert system in which we have tried to represent the strategy of the NATO commander.

Undertaking both of these kinds of analyses in our laboratories gives us a way to calibrate the expert systems and see if we are capturing the sorts of variations that occur when real players make decisions. We have also examined the kinds of political decisions that would accompany the escalation from limited, conventional war to geopolitical conflict.

Strategic Defense Analysis

There are no expert systems involved in our Strategic Defense Initiative (SDI) analyses of several experimental architectures. However, this work demonstrates the vital contribution of graphics to the analytic endeavor. This particular example entailed some very detailed analyses of a launch from a number of Soviet ICBM silos and SLBM submarines. We knew the approximate number of missiles that would be launched, and computed the missiles' trajectories to the United States against a distributed target base. Then, against those launches, we put up a number of illustrative SDI systems. For example, one architecture consisted of roughly 20,000 satellites in polar orbits,

with each satellite carrying one rocket-propelled interceptor. We wanted to see how effective this type of system would be against the boost phase of missiles launched from Soviet silos and submarines, and we wanted to see what kinds of patterns those satellites achieved during the engagement process.

Color Plate 6 shows "nadir position" or the position of the satellites over the earth at the moment of launch of the missiles. Color Plate 7 shows the satellites that would be involved in the boost-phase intercept and those which have achieved fire-control intercept position. These geometries are non-intuitive and difficult to grasp without visual display. An ordinary computer printout of these results would leave the analyst with a tower of paper to peruse for that set of numeric data now automatically processed and presented on a graphics terminal.

One important SDI issue is the "defense suppression attack" against these satellites. That is, what if the Soviet Union decided that before launching their ICBMs, they would take out all of the relevant defending satellites by some combination of prior launch and anti-satellite (ASAT) activity? Because there are thousands of numbers in this kind of simulation, it is extremely difficult to determine the critical patterns by just looking at the numbers. But by using our three-dimensional graphics capability at relatively high resolution (we have very high performance equipment--500,000 vector-per-second graphics engines), the analyst can rapidly see patterns and note, for example, that most of the satellites that would be involved in the defense would not be over the Soviet Union just before the attack. In other words, with this particular defense architecture, a simple defense suppression attack would be extremely difficult.

For this simulation, we have combined orbital mechanics models and ICBM trajectory analysis models. The SDI analysis demonstrates how our coupling of state-of-the-art graphics to our models and to our simulations gives the analyst new and powerful tools.

Tactical Command and Control and Electronic Battle Simulations

Detailed simulations of tactical command and control and electronic battles have very large computational requirements and are conceptually difficult to model. ROSS, developed at RAND to accommodate these kinds of complicated simulations, is an object-oriented simulation language written using LISP.

Color Plate 8 shows a detailed computer graphics view of terrain in a 25 by 50 km area of central Europe at the intra-German border. The data, which are from the Defense Mapping Agency, have about 3-meter resolution and show not only the terrain, in this case the river valleys, but also the forestation around those areas and the road network. The research questions here are (1) how do units actually move through real-world conditions, (2) what can we see of the surrounding area, given our advanced sensors, and (3) how can we evaluate the use of advanced sensors and intelligence to help us do a better job in combating the Warsaw Pact?

The six objects (light blue dots) in the lower right-hand corner of Color Plate 8 represent small groups of tanks moving along the road. We wish to find out how well our intelligence sensors could monitor that movement. In a procedural programming system, the programmer would have to decide exactly which path each one of these units would take, and build that decision into the input files. This requirement makes running such a simulation very tedious. We have circumvented this problem by using ROSS and coupling it with expert systems. The analyst only need say, "I want these units to go to their end positions," which he will specify, and the computer program will compute, from a rule-based system, the best route and the optimal order for the units to move through the road system. The program performs line-of-sight calculations and terrain analysis. All the communication rules involved in each unit's move are important parts of the simulation because each radio communication is an opportunity for an electronic intercept.

Color Plate 9 shows what a representative airborne radar system could be expected to observe of this activity through real terrain. In this case the radar is about 150 km away from the intra-German border, looking with moving-target-indication radar so as to communicate line-

of-sight information to all ground units. What that radar is actually able to see is a region of visibility revealing detailed terrain and the road network. The areas it cannot see, because they've been masked by foliage or by the terrain itself, are shown in grey. One of the disturbing conclusions from this kind of analysis is that at a moderate distance behind the intra-German border, the radar does not see very much. In fact, much of the time it will be completely obscured and unable to observe the movement of our own or of enemy troops through the area. We want to experiment with various altitudes for better view factors but must consider tradeoffs of visibility for vulnerability.

Because we are interested in what kind of information advanced sensors in units can provide, the system also computes what it is able to see on the ground. Color Plate 10 shows what a particular unit, looking around 360 degrees, can see. The areas in grey are blocked because of terrain, and the areas in white are blocked because of foliage and forest area. It is apparent that in this particular area of Germany, the unit does not have very good visibility.

This type of simulation is extremely computationally intensive. We have been discussing only six objects. In another version of this simulation we might have to consider some 500 objects. That type of simulation would be much slower than real time, and the analysis would be correspondingly slow. The need for greater processing speed prompted us to experiment with Time Warp, an operating system that uses multiple computers and promises an order of magnitude increase in speed by coupling perhaps 10 microprocessors over a local area network. We are hoping that this operating system will yield up to 30 million operations per second--roughly the power of a CRAY computer from about $200,000 worth of computer hardware. If we are successful, it will give the analyst much more powerful use of relatively inexpensive computer tools.

Time Warp exemplifies the fruitful application of RAND seed money in the information sciences. The project was initially funded by RAND research funds, and has now been sponsored by the Army as a three-year research effort on tactical problems of the kind described above.

III. FUTURE RESEARCH

Four issues suggest that RAND has reached a turning point in simulation technology, leading to new challenges in information sciences research. Much of this research will involve new database structures, integrating artificial intelligence techniques with both databases and user-computer interfaces.

- First, current systems are improving but are still too slow for many large-scale, high-payoff applications. We need to increase computation speed by several orders of magnitude.
- Second, we know that there is a large amount of uncertainty in both inputs and outputs of our simulations, and we need to run many different cases to get some sense of the range of outputs. But we cannot do all the "what ifs" we want unless the systems work very quickly and very cheaply.
- Third, large-scale simulations for policy analysis must be transparent to the analyst: Any good analyst is suspicious of assumptions that are buried in computer code. This means that the code must be easy for the non-computer expert to read and use. We must seek greater transparency through better integration of models, graphics, expert knowledge, and databases.
- Finally, we need systems that are easier to document, modify, and use. We must find better ways to present the information that results from new computer tools.